PB85-218816

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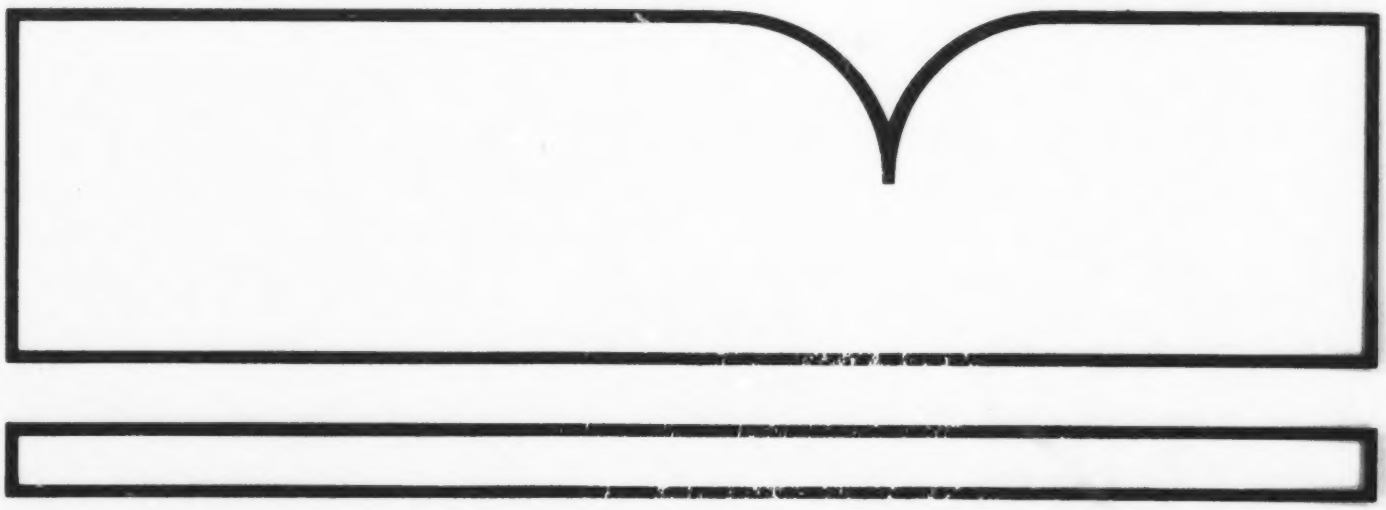
(U.S.) Environmental Protection Agency
Research Triangle Park, NC

1985



U.S. Department of Commerce
National Technical Information Service
NTIS

EPA/600/D-85/132
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Emission Control Effectiveness of a Woodstove Catalyst and Emission Measurement Methods Comparison

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Abstract

Emissions were measured on a prototype catalytic and a generic noncatalytic stove over a range of burnrates. The stoves were operated in a calorimeter room according to Oregon certification procedures. For the catalytic stove, simultaneous EPA Modified Method 5 (MM5) samples were obtained before the catalyst and in the stack. For both stoves, Oregon Method 7 (OM7) and Condar® dilution samplers (CDS) were operated simultaneously with the MM5 train at the stack location. Volatile organic samples were obtained by integrated bag sampler at the stack location. Results show a generally predictable correlation between MM5, OM7, and CDS results. Emission rates, based on MM5, were approximately twice those based on OM7 and CDS. Catalyst emission reduction effectiveness (by MM5) ranged from 72 to 98%. Catalyst inlet emissions appear to be affected by the test sequence; a high burnrate test produced higher emissions when preceded by a low burnrate test than when preceded by a high burnrate test. Volatile organic emissions were about the same at all burnrates on the catalytic stove and at low burnrates on the noncatalytic stove. At a high burnrate, the noncatalytic stove produced substantially less. All MM5 samples tested positive for polynuclear aromatic hydrocarbons.

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA/600/D-85/132	2.	3. RECIPIENT'S ACCESSION NO. PB85 218816/AS
4. TITLE AND SUBTITLE Emission Control Effectiveness of a Woodstove Catalyst and Emission Measurement Methods Comparison		5. REPORT DATE 1985
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert C. McCrillis and Raymond G. Merrill		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS See Block 12.		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. NA (Inhouse)
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Published Paper; 5/85
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Robert C. McCrillis, Mail Drop 54, 919/541-2733.

16. ABSTRACT The paper gives results of measurements of emissions from a prototype catalytic and a generic noncatalytic stove over a range of burnrates. For the catalytic stove, simultaneous EPA Modified Method 5 (MM5) samples were obtained before the catalyst and in the stack. For both stoves, Oregon Method 7 (OM7) and Condar dilution samplers (CDS) were operated simultaneously with the MM5 train at the stack location. Volatile organic samples were obtained by integrated bag sampler at the stack location. Results show a generally predictable correlation between MM5, OM7, and CDS results. Emission rates, based on MM5, were about twice those based on OM7 and CDS. Catalyst emission reduction effectiveness (by MM5) ranged from 72 to 98%. Catalyst inlet emissions appear to be affected by the test sequence: a high burnrate test produced higher emissions when preceded by a low burnrate test than when preceded by a high burnrate test. Volatile organic emissions were about the same at all burnrates on the catalytic stove and at low burnrates on the noncatalytic stove. At a high burnrate, the noncatalytic stove produced substantially less. All MM5 samples tested positive for polynuclear aromatic hydrocarbons.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Organic Compounds Stoves Wood Combustion Catalysis Measurement	Pollution Control Stationary Sources Woodstoves	13B 07C 13A 11L 21B 07D 14G

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	18
	20. SECURITY CLASS (This page) Unclassified	22. PRICE $7.00

EPA Form 2220-1 (9-73)

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Introduction

Residential wood combustion (RWC) has become a significant air pollution source over the past 10 years contributing to marked increases in ambient particulate levels in many communities during winter months. Air pollution regulatory authorities in EPA, several states, and numerous communities have undertaken regulatory development programs aimed at reducing RWC ambient air quality impacts. A major consequence of these regulatory programs is the proliferation of stoves incorporating a precious metal catalyst to promote improved combustion of the carbon monoxide and organic compounds released from the oxygen starved primary combustion zone. Originally introduced into the market several years ago on the basis of improved energy efficiency and reduced chimney fire hazard, the catalysts are now also being looked upon as offering significant control of woodstove emissions. Published catalytic stove emissions data indicate that, when new, the stoves can achieve particulate emission rates far below the level of typical conventional stick-fired stoves[1]. Very little data exist which address the long-term emission control effectiveness of these catalysts.

This paper addresses the results of the first phase of an EPA project whose major goals are to (1) define the effect of woodstove catalysts on the mutagenic/carcinogenic components of woodsmoke and (2) determine how this effect varies as a function of catalyst age. Integral to these goals is the development and comparison of sampling and analysis methodologies. Specifically, this paper presents the results of seven emission tests on a catalytic stove and two on a noncatalytic stove. On the catalytic stove, simultaneous samples were obtained using EPA Modified Method 5 (MM5)[2] before and after the catalyst. On both stoves, collocated Oregon Method 7 (OM7)[3] and Condar® dilution sampler (CDS)[4] trains were run simultaneously with the MM5 train at the stack location to develop a comparison between the latter two particulate sampling methodologies and MM5. Samples for volatile organic compound analysis were also obtained at the same stack location.

Experimental Methods

The following discussion is divided into three main topics. First is a description of the test facility and the stoves tested. Second is a description of the emission measurement methodologies employed. The third main topic is a discussion of analytical procedures.

Test Facility

All emission tests were performed at OMNI Environmental Services, Inc.'s calorimeter room woodstove test facility in Beaverton, OR, during the period August 27-31, 1984. OMNI's facility, previously described in detail[5,6], consists of a calibrated calorimeter room and all associated controls and instrumentation. A calorimeter room allows one to determine the heat output of a stove by measuring all energy entering the room including that in the fuel and all energy leaving the room including that in the stack gas and that transferred to the room.

The prototype airtight catalytic stove tested has a 20.3 cm stack diameter (top exit) with a usable firebox volume of 0.07 m^3. The bottom of the

firebox is lined with brick with additional brick on the sidewalls to a height of 30 cm and on the rear wall to a height of 20.3 cm. Primary combustion air enters through a thermostat control located at the rear of the unit and enters the firebox through the rear wall at a height of 12.7 cm. Secondary air enters an air distributor directly below the catalytic combustor (at the top of the firebox). The secondary air is preheated as it passes through the gas plenum above the combustor. The unit can be operated in a catalyst bypass mode, but for the purpose of this testing the bypass was closed, except when loading fuel. There is a fan mounted on the rear of the unit that forces air between the heat shields of the unit and out the front through a series of slots.

The noncatalytic airtight radiant step-top stove tested has a 15.24 cm stack diameter (top exit) and a usable firebox volume of 0.068 m^3. The bottom of the firebox is lined with brick with additional brick on the side and rear walls to a height of 20.3 cm. Combustion air enters through a spin draft located on the door of the unit (eight holes, 1.27 cm in diameter). There is a baffle plate extending across the rear wall of the stove about 33 cm above the firebox floor. The baffle plate is 10.2 cm wide and slopes up toward the flue collar.

Emission Measurement Methods

Three different sampling trains were used to measure particulates (including semivolatile and condensible organics): EPA Modified Method 5 (MM5), Oregon Method 7 (OM7), and Condar® dilution sampler (CDS). The three sampling trains are described briefly in the following paragraphs.

Modified Method 5. The MM5 train[2] consists of a heated, glass-lined probe, heated glass filter holder with fiberglass filter, indirect water-cooled condenser, XAD-2 porous polymer resin trap, and a series of four impingers in an ice bath. The sampling portions of the train are followed by a vacuum pump, dry gas meter, and associated control electronics. Two MM5 trains were operated simultaneously, one immediately before the inlet side of the catalyst, the other in the chimney about 2.4 m above the stove base.

Oregon Method 7. The OM7 train[3] is similar to MM5 but differs in that the condenser and XAD trap are not used. A second unheated filter holder is placed between the third and fourth impingers. One OM7 train was operated simultaneously with the MM5 train at the 2.4 m chimney location.

Condar® Dilution Sample. The CDS[4] is quite different from either of the above trains. The unit consists of a very short sampling probe, a dilution chamber with integral filter holder, and a vacuum pump. Dilution air, entering through holes in the upstream end of the chamber, mixes with and cools the emission sample prior to filtration. One CDS was operated simultaneously with the MM5 and OM7 trains at the 2.4 m chimney location.

Particulate material including ash and condensed organic material was collected to some extent in each of the sampling systems. Only the MM5 train uses technology specifically designed to efficiently collect organic material which passes through the filter media used in all three sampling trains.

Both the MM5 and the OM7 approaches extract organic material from the impinger catches.

Volatile Organics. Samples for volatile organic compounds analysis were collected by a lung sampler similar to EPA Method 106 and are reported here as C_1-C_7 hydrocarbons. For both stoves, volatile organic samples were taken from the stack at approximately the same location used for MM5/OM7/CDS sampling. Samples were extracted at a rate of 100 ml/min throughout a given test.

Gases. Continuous measurements of CO and CO_2 were made using NDIR devices meeting the Oregon Certification Procedure Criteria. Oxygen was measured at 15 minute intervals. The volatile organic samples provided an independent measurement of the average CO, CO_2, and O_2 concentrations for each test.

Analytical Procedures

Modified Method 5. The MM5 train operation and sample recovery in general followed published procedures[2]. Some modifications were instituted to tailor MM5 to woodstove emission sampling. The principal modifications were:

(1) Sample rate was held constant; no attempt was made to sample isokinetically.
(2) All samples were taken from a single point; there was no traversing.
(3) No precutter cyclone was employed.
(4) Sample recovery and subsequent extractions utilized both dichloromethane ($MeCl_2$) and methanol (MeOH) solvents. In all cases, the rinses and extractions were kept separate (i.e., $MeCl_2$ and MeOH probe rinses were done sequentially and placed in separate containers).
(5) All recovered liquid samples were placed in amber glass jars and sealed with Teflon cap liners.
(6) All recovered samples were frozen immediately, packed in dry ice for shipment, and subsequently stored at 0°C.

Modifications 1-3 represent common practice when sampling woodstove emissions. Modification 4 was made to ensure complete sample recovery while preserving sample quality. Woodstove emissions are not completely soluable in $MeCl_2$, the preferred solvent for subsequent organic analyses. MeOH would remove all remaining residues and, although it might, itself, react with organics in the emissions, would permit a more accurate estimate of total emission. Samples recovered from MeOH washes were used for mass determinations only. Modification 5 was instituted to minimize sample contamination. Modifications 5 and 6 were employed to minimize sample degradation caused by ultraviolet radiation or heat.

A representative sample of organic material is collected in the MM5 train in three portions. These three discrete samples from the MM5 train were processed individually for chemical analysis in the studies reported here to determine how much and what kind of material from the emissions were collected in each part of the train. (For routine work, the complete train can be treated as a single sample.) One sample often referred to as the front half comes from the probe wash, filter housing wash, and filter. The second sample

comes from the XAD-2 sorbent and sorbent module wash. The final sample comes from the condensate and condensate impinger rinse. For the results in this report, rinses were performed with both dichloromethane and methanol.

Gravimetric determinations (weighings) were conducted on the filter, filter housing wash, and probe wash before extraction to determine the particulate/condensed organic loading in the front half of the train.

Chemical analyses of extracts of the collected samples were conducted to determine the extractable organic material (EOM). To generate the EOM, two analyses were performed. A gravimetric analysis (GRAV) of an aliquot of each extract was used to quantify the organic material which had a boiling point greater than 300°C. A gas chromatographic analysis (TCO) was performed on samples to determine the amount of material with boiling points in the range of 100 to 300°C.

Oregon Method 7. Procedures for sampling, sample recovery, and analysis followed the standard procedure authorized by the State of Oregon[3]. In this procedure, the flue gas sample extraction rate is maintained at a fixed proportion of the flue gas velocity. Sample recovery includes washing all train components with acetone. Impinger solutions are extracted first with chloroform and then diethyl ether; the extracts are then combined. Filters and solvent washings/extractions are desiccated at 21°C or less.

Condar®. The CDS utilizes back-to-back fiberglass filters as the collection media. During a burn both filters were changed every 30 minutes as specified by Condar, Inc. in the operating procedures supplied with the CDS. At the conclusion of a burn the filters were desiccated at laboratory conditions and then weighed individually and in corresponding pairs.

Volatile Organics. The integrated bag samples collected during each burn were analyzed by GC/MS using a 2.44 m (2 mm ID) column filled with 1% SP1000 on 60/80 mesh Carbopack B packing. The column was temperature programmed from 20 to 220°C at 10°C/minute after a 1 minute initial temperature hold. The instrument was calibrated using a 360 ppm propane-in-nitrogen mixture. Response to benzene and toluene was calculated by multiplying the propane response by 1.12. Rate of loss through the Tedlar bag wall was determined by reanalyzing a sample 5 days after the first analysis. The 360 ppm propane calibration bag lost 5.1% over the same 5 days as determined from five repetitive analyses. Quality assurance audit samples, supplied by one of EPA's QA contractors (Research Triangle Institute) revealed a consistent 20% low bias in the measurements. The source of this error could not be discerned. It is possible that the results presented here underestimate the actual volatile organic emission rates by as much as 20%.

Results

The results of the series of nine burns performed are presented in this section. Appliance operation is discussed first followed by presentation of the emission measurements including comparison of the results obtained by the three particulate/organic sampling methods employed.

Appliance Operation

The appliances were operated according to the Oregon Certification Procedure during all burns. Average fuel and appliance operating parameters are shown in Table I. Burns were performed on the catalytic stove at low, medium, and high burnrates; the noncatalytic stove was tested at low and high burnrates only. Note that catalyst No. 7 was used for Burn 1 only. Catalyst No. 7 appeared to be ineffective, so it was replaced with catalyst No. 4 for Burns 2-7. The catalysts used are described in Tables II and III. Burns 2-7 on the catalytic stove and 8-9 on the noncatalytic stove were run one after the other following removal of ash from the previous burn. No attempt was made to remove accumulated deposits in the stove and flue pipe between runs.

Flue gas conditions are summarized in Table IV; Table V summarizes the efficiency and heat output. Every attempt was made to maintain identical operating conditions during replicate runs. Burns 1, 2, and 7 can be compared to see the effect, if any, of the change in catalysts. Burn 2 produced an overall efficiency of 66.7% compared to 62.0% in Burn 1; both combustion and heat transfer efficiencies were higher in Burn 2. The increase in combustion efficiency could well be due to improved catalyst activity. Burn 7 also shows some improvement in overall efficiency relative to Burn 1; however, the combustion efficiency was actually 1.1 percentage points lower. Subsequent to Burn 2 it was noted that the stove's secondary air draft control was at a reduced airflow setting compared to the normal procedure followed for this appliance. During the replicate run, Burn 7, the secondary air control was set in the normal position. Comparing these two burns (2 and 7) in Tables IV and V, it can be seen that the stove operated more efficiently in Burn 2 although the heat output was slightly lower due to a lower burnrate (see Table I). On the surface, these data do not show any significant differences in efficiency related to the catalyst change.

Following the conclusion of Burn 4, it was noted that the catalyst bypass damper appeared to be leaking due to debris lodged on the lip of the damper. It was assumed that this condition had existed only for Burn 4. Comparing Burn 4 to its replicate, Burn 3, it can be seen in Table IV that the oxygen content, carbon monoxide content, and excess air were lower, while the CO_2 content was higher for Burn 3, indicating more efficient combustion. Table V verifies this indication.

Emissions Results

The following discussion includes (1) comparisons between MM5, OM7, and CDS results; (2) analysis of catalyst emission control performance; (3) results of polynuclear aromatic hydrocarbon screening tests; and (4) volatile organic compound measurements in the stack.

Emissions from woodstoves should not be viewed as particulate material but rather as predominantly organic material covering a wide range of volatility. Almost 100% of the emissions measured by the techniques used in this study have been shown to be organic material which can be dissolved or extracted with the appropriate organic solvent. During woodstove operation the organic material with low volatility (high boiling point) condenses as it rises and cools in the appliance flue. The resulting tar forms an aerosol which

behaves like a particle. These minute droplets are predominantly less than or equal to 1 um dia. The particulate emissions referred to in woodstove test reports are, in fact, mostly captured semivolatiles and condensible organic aerosol. Therefore, the temperature of the flue and the temperature at which the sample was collected make a profound difference on the quantity of material labeled "particulate emissions."

Methods Comparisons - Front Half. MM5 collects ash and low volatility (condensible) organic material on a filter heated to 125°C. The identical technique is used for OM7 front filter sample collection. Material adhering to the inside of the sampling train from the probe tip to the filter is removed during sample recovery and counted as part of the front half catch for both MM5 and OM7. A comparison of the MM5 and OM7 front half results is shown in Figure 1. The MM5 front half is consistently larger than for OM7 due, probably, to the difference in sample rate. MM5, at a filter face velocity of 0.3 cm/sec, would retain more organics on the filter than OM7 at 1 cm/sec average filter face velocity. In addition, more material would stick to the MM5 probe as a result of the lower sample rate. The two techniques appear to correlate quite closely.

The CDS collects ash and condensed organic material on a set of ambient temperature filters. There is no back half; front half equals the total train. Because of the lower collection temperature, the CDS samples should contain more mass than the hot MM5 or OM7 filter if filter face velocity were the same for all three. Figure 1 shows that the CDS collects substantially less than MM5 which indicates that filter face velocity may be a dominant effect. CDS filter face velocity averaged 5 cm/sec. This comparison is somewhat clouded by the fact that the CDS uses a very short sample probe. No attempt is made to recover sample from the probe or the walls of the dilution chamber. In spite of these differences, the CDS appears to correlate fairly well with the MM5 front half.

Methods Comparison - Total Train. Organic materials not retained on the heated filter are dealt with differently in the MM5 and OM7 sampling trains. MM5 employs a cooling coil (held at 20°C or less) and a porous polymer sorbent (XAD-2). The efficiency of the XAD-2 sorbent trap to collect and retain organic material with boiling points greater than 100°C is well documented[2]. The OM7 train employs an impinger system immersed in ice water, and a final cool filter to collect condensible organic vapors. The ability of the aqueous impinger used in OM7 to collect semivolatile material is not well documented. In addition, no provision is made during sample recovery for retention or analysis of semivolatile organic material with boiling points lower than 300°C in the OM7 procedure (i.e., only materials remaining after air drying of the samples are weighed using the OM7 procedure).

It is apparent from the comparisons shown in Figure 2 (see also Table VI) that the MM5 total train emission rates are approximately twice the OM7 total train and CDS emission rates. OM7 total train and the CDS correlate quite well with MM5 total train. It also looks as if the correlation might be stove-type dependent; however, this data base is too small to draw a firm conclusion.

Catalyst Performance. The MM5 total train results before and after the catalyst are compared in Figure 3. At first glance, Burns 5 and 7 appear to

have anomalously higher catalyst inlet emissions. However, the variability seen might be attributed to the order in which the burns were run. Each time a burn was preceded by one at a lower burnrate, the second burn produced significantly higher emissions entering the catalyst. Conversely, when a burn was preceded by one at the same or higher burnrate, catalyst inlet emissions levels were relatively low. Two examples are:

> Burn 5 vs Burn 4 - Burn 5, at a medium burnrate, showed nearly 4 times the catalyst inlet emission compared to Burn 4, at a low burnrate.
>
> Burn 3 vs Burn 2 - Burn 3, at a low burnrate produced less catalyst inlet emissions than did Burn 2, a high burnrate test.

As noted previously, the stoves and flue were not cleaned between tests other than normal ash removal. Thus, organic material which condensed onto the interior stove and flue surfaces during one burn was there at the start of the next one. If the next burn was at a higher burnrate (temperature), some of this condensed material would be revolatilized until a new equilibrium deposition/revolatilization rate was established.

Catalyst outlet emissions tend to show a similar test sequence effect. The effect is not as discernible as in the inlet case due to the confounding effect of the catalyst. A high emission concentration entering the catalyst might have improved the combustion parameters sufficiently to yield less emissions in the stack.

Looking at Burns 2, 3, 4, and 6 (Figure 3), tests where the hypothetical burn sequence effect would not have influenced results, it seems that the catalyst inlet emissions remained fairly constant over the range of burnrates tested. Including Burns 8 and 9 in this comparison indicates that both stoves generated emissions at about the same rate; however, this may be a coincidence since stove-to-stove variability is well documented[1].

Catalyst No. 4 emission control effectiveness as measured by MM5 ranged from 72 to 98%, with an overall average of 89% for the six burns.

Recalling that catalyst No. 7, used only in Burn 1, did not appear to be functioning properly, it is of interest to look at the catalyst effectiveness for Burns 1 and 2. Emission reductions for Burns 1 and 2 were 26 and 89%, respectively. Thus it is obvious that catalyst No. 4 was much more effective.

Analysis of TCO to GRAV (semivolatile to condensible) ratios before and after the catalyst indicates that this ratio tends to increase across the catalyst (see Table VII and Figure 3). Four of the six burns using catalyst No. 7 show an increase; three burns showed an approximate doubling. This indicates that the catalyst is more effective on the heavier GRAV component and/or that some of the GRAV material is pyrolized into lighter compounds. Going one step further, the following catalyst inlet to catalyst outlet TCO/GRAV ratios indicate that the catalytic stove tested tended to generate larger quantities of lighter compounds at both low and high burnrates compared to a medium burnrate.

Whether this trend is generally applicable or peculiar to this particular stove or even just this test series is not known.

Burnrate	Catalytic $\frac{(TCO/GRAV)_o}{(TCO/GRAV)_t}$	Noncatalytic TCO/GRAV
Low	1.495	1.2
Medium	0.965	---
High	2.015 (excluding Burn 1)	0.74

PAH Screening Test Results. Each part of the recovered MM5 samples was screened for polynuclear aromatic hydrocarbons (PAH). The method used, PAH Spot Test, has been shown to be quite selective for PAH; sensitivity is on the order of 10-100 pg/ul of extract.(7) The results for the 16 MM5 runs are as follows:

MM5 Train Component	Positive/Negative
Front $MeCl_2$ rinse	15/1
Front MeOH rinse	12/4
Filter $MeCl_2$	16/0
XAD-2 $MeCl_2$ extract	15/1
Condensate $MeCl_2$ extract	0/13[a]
Impinger $MeCl_2$ extract	added to XAD-2 extract
Impinger MeOH extract	no spot test

[a]Three condensate samples were lost

The MM5 room air blank sample gave positive results for the XAD-2 and the impinger $MeCl_2$ extracts. No condensate sample was collected during acquisition of the room air blank. All solvent and filter laboratory blanks checked negative.

Additional PAH analyses in progress include total PAH quantification and quantification of selected PAH compounds. These results will be reported at a later date.

Volatile Organics. Table VI includes a summary of total volatile organics reported as nonmethane C_1-C_7 hydrocarbons. Burn 2 showed less volatile hydrocarbons relative to Burn 1 which is consistent with the MM5 results. However, Burn 7 also showed less than Burn 2, the opposite from all earlier results. Burn 5, at a medium burnrate, showed a low rate which is consistent with the low TCO/GRAV ratio. The high burnrate (Burn 9) on the noncatalytic stove produced the lowest volatile hydrocarbon emission rate. In general, it would seem that volatile organic compound emission rates for the catalytic stove increased as the burnrate increased whereas the oposite appears to be the case for the noncatalytic. At low burnrates, the noncatalytic stove emission rate was about the same as the catalytic's. At high burnrates, these data suggest that the noncatalytic stove emitted less volatile organics compared to the catalytic device. This result is rather surprising. It would seem that the catalytic stove produced substantially more of these compounds

in the primary combustion process, that the catalyst was relatively less effective at promoting secondary combustion of these light organics compared to its effectiveness on the heavier compounds, and/or that some of the heavier TCO and GRAV compounds were broken down into light organics during passage through the catalytic combustor. Analysis of simultaneous before and after the catalyst volatile organic samples would shed more light on this question.

Summary and Conclusions

The preceding discussion leads to the following conclusions:

a. In general, there appears to be a predictable relationship between emissions as measured by MM5, OM7, and CDS.

b. There appears to be a test sequence effect on emissions. A high burnrate test preceded by one at a low burnrate appeared to generate higher emissions than when preceded by a test at the same or higher burnrate.

c. Emission rates (by MM5) entering the catalyst were similar to atmospheric emission rates from the noncatalytic stove for burns where the test sequence effect was not apparent.

d. Catalyst emission reduction averaged 89% as measured by MM5.

e. The ratio of semivolatile (TCO) to condensible (TCO) organic compounds tends to increase across the catalysis. Volatile organic emissions after the catalyst at all burnrates are about the same as for the noncatalytic stove at low burnrates. At higher burnrates, the noncatalytic stove emitted substantially less volatile organics. In toto, this suggests that, for the stove tested, either the catalyst preferentially promoted oxidation of the heavier (GRAV) organics (which seems unlikely) or the heavier organics are broken down into lighter compounds during passage through the catalyst. Generalization to other catalytic stoves cannot be made without additional data.

f. All MM5 train component extracts from the probe through the XAD-2 showed the presence of PAHs. No PAH was detected in components tested after the XAD-2.

Acknowledgements

Lawrence E. Cottone, Engineering Science, was the field sampling project manager and operator of the MM5 equipment. The OMNI Environmental Services staff, under the direction of Paul E. Tiegs, operated the stoves, calorimeter room, and the OM7 and Condar® equipment. OM7 samples were recovered and results calculated by OMNI. Stockton G. Barnett, Condar Company, reduced the CDS data. MM5 sample recovery and analysis were performed by Acurex personnel under the direction of Leonard Nelms. Volatile organic compound analyses were performed by Crown Zellerback Environmental Services.

ENDNOTES

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Table I. Fuel and appliance operating parameters.

BURN	BURN RATE kg/hr[a]	FUEL H_2O, %[b]	HHV[c] kJ/kg	TEST DURATION minutes
1	3.33	18.31	19976	130
2	2.74	18.05	19580	170
3	0.68	17.56	19636	725
4	0.84	18.56	19769	535
5	1.46	18.58	19345	300
6	1.71	18.99	19438	270
7	2.94	18.23	19764	150
8	1.10	18.10	19327	420
9	4.75	17.83	19687	90

(a) Kilograms per hour of wet wood
(b) Fuel moisture content as percent of wet wood weight
(c) Higher heating value, kJ/kg of wet wood
(1 kJ/kg = 2.326 Btu/lb)

Table II. Catalyst No. 7 record (used on Burn 1).

16 cells/in.^{2} (2.5/cm^2)
6 in. (15.24 cm) in diameter
3 in. (7.62 cm) in depth
Manufacturer: Corning
Total hours used (including these tests) = 97

Table III. Catalyst No. 4 record (used on Burns 2 through 7).

25 cells/in.^{2} (3.88/cm^2)
6 in. (15.24 cm) in diameter
3 in. (7.62 cm) in depth
Manufacturer: Corning
Total hours used (including these tests) = 488.5

Table IV. Flue gas measurements.

BURN	TEMP, °C	H_2O, %	O_2, %	CO_2, %	CO, %	EX AIR, %	Nm^3/hr	DRAFT, mm H_2O	AIR/FUEL
1	158	14.32	6.82	13.30	1.42	54.38	0.280	-1.448	7.66
2	115	17.11	6.43	13.40	1.23	41.59	0.239	-1.219	7.92
3	52	8.13	11.08	9.17	0.54	112.90	0.091	-0.508	12.02
4	51	7.67	12.26	7.86	0.76	135.42	0.124	-0.533	13.58
5	88	11.75	9.03	11.14	0.42	77.04	0.163	-0.838	10.21
6	83	12.77	8.09	12.17	0.70	76.53	0.166	-1.016	8.93
7	111	14.30	8.56	11.15	1.77	67.94	0.287	-1.346	8.85
8	83	10.27	13.14	6.33	3.00	156.43	0.140	-0.762	11.51
9	254	14.62	6.77	13.02	2.11	60.99	0.391	-1.575	7.44

Table V. Efficiency and heat output.

BURN	THERMAL EFFICIENCIES			HEAT OUTPUT
	COMBUSTION, %	HEAT TRANSFER, %	OVERALL, %	kJ/hr[a]
1	82.8	74.8	62.0	33,682
2	85.9	77.6	66.7	29,353
3	88.8	88.5	78.6	8,658
4	87.4	83.2	72.7	9,820
5	90.5	79.5	71.9	16,577
6	86.9	77.3	67.1	17,950
7	81.9	78.0	63.9	30,409
8	67.2	78.0	52.5	9,186
9	79.8	67.7	54.0	41,496

[a]kJ/hr (1 kJ = 1.05587 Btu)

Table VI. Emissions summary.

BURN	TEST LOCATION	BURN RATE	EPA MM5	OREGON OM7	CONDAR DILUTION	TOTAL NON-CH_4 VOL. ORGANICS	STOVE TYPE
		kg/hr	----------Particulates, g/hr----------				
1	INLET	3.33	51.677				Catalytic
2	INLET	2.74	78.393				"
3	INLET	0.68	51.559				"
4	INLET	0.84	55.009				"
5	INLET	1.46	197.380				"
6	INLET	1.71	50.023				"
7	INLET	2.94	173.543				"
1	STACK	3.33	37.894	18.100	9.391	19.68	"
2	STACK	2.74	8.661	3.800	1.726	13.40	"
3	STACK	0.68	1.980	1.100	0.932	1.19	"
4	STACK	0.84	9.111	9.200	5.922	2.34	"
5	STACK	1.46	3.805	3.600	2.015	1.85	"
6	STACK	1.71	2.905	3.900	2.633	----[a]	"
7	STACK	2.94	48.040	24.400	11.789	5.70	"
8	STACK	1.1	51.277	42.000	36.542	3.74	Noncatalytic
9	STACK	4.75	73.404	44.600	22.705	0.52	"

[a]Burn 6 sample not analyzed.

Table VII. MM5 train breakdown.

BURN	NON EXT[a]	TCO[b]	GRAV[c]	TOTAL	TCO/GRAV	SAMPLING LOCATION
	---------- g/hr ----------					
1	0.049	24.597	27.080	51.726	0.908	INLET
1	0.010	17.203	20.681	37.894	0.832	STACK
2	0.101	39.635	38.657	78.393	1.025	INLET
2	0.002	5.848	2.811	8.661	2.080	STACK
3	0.131	25.842	25.586	51.559	1.010	INLET
3	0.001	1.109	0.870	1.980	1.275	STACK
4	0.015	22.000	32.994	55.009	0.667	INLET
4	0.014	4.877	4.220	9.111	1.156	STACK
5	0.301	111.506	85.573	197.380	1.303	INLET
5	0.005	2.109	1.691	3.805	1.247	STACK
6	0.021	19.409	30.593	50.023	0.634	INLET
6	0.002	1.098	1.805	2.905	0.608	STACK
7	0.108	89.380	84.055	173.543	1.063	INLET
7	0.023	32.661	15.356	48.040	2.127	STACK
8	0.008	27.935	23.334	51.277	1.197	STACK
9	0.039	31.175	42.190	73.404	0.739	STACK

[a]Non-extractable
[b]Total chromatographable organics
[c]Gravimetric

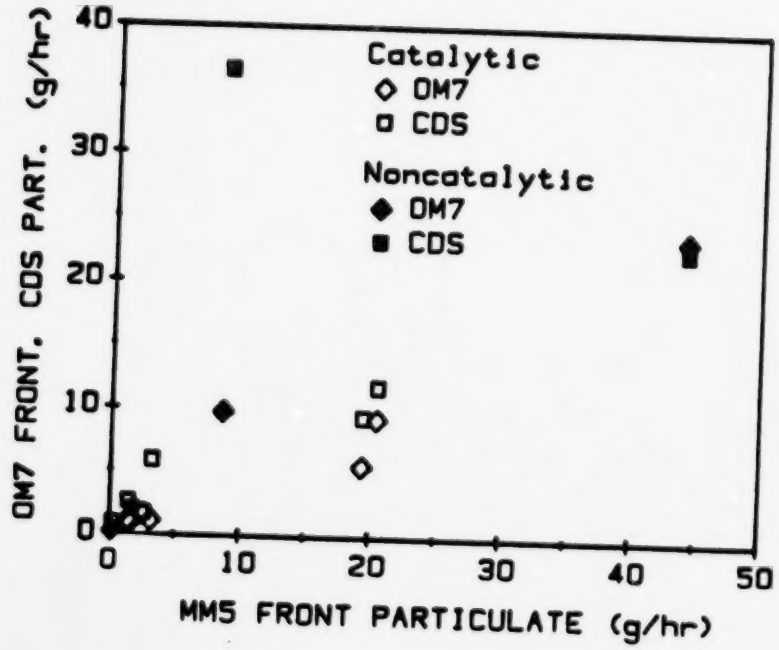

FIGURE 1. MM5 and OM7 Front Half, CDS Total Comparison

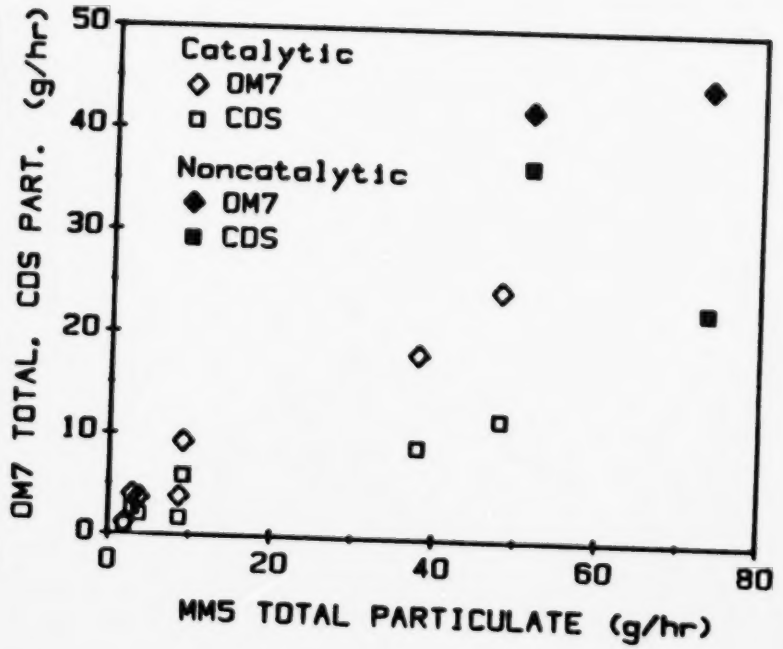

FIGURE 2. MM5, OM7, and CDS Total Train Comparison

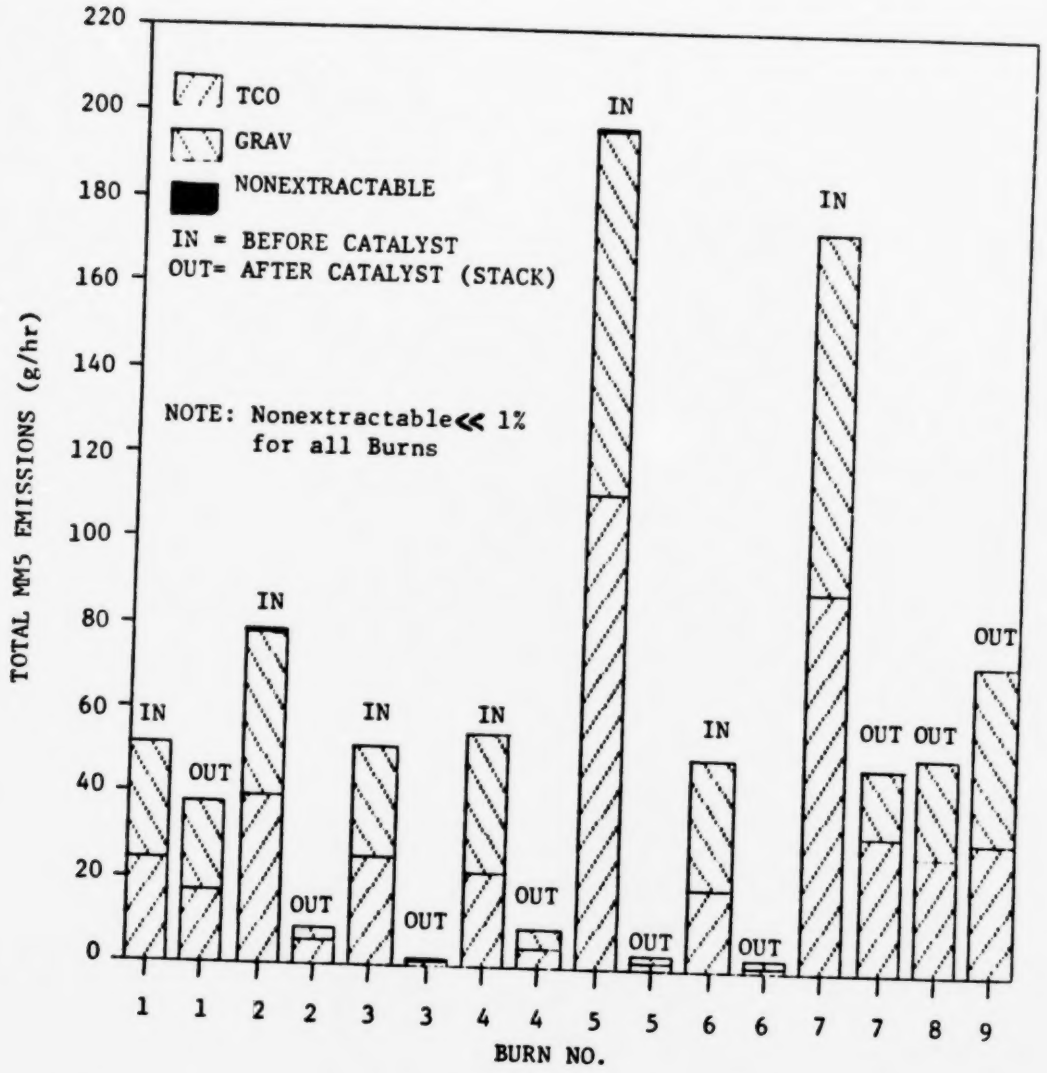

Figure 3. Modified Method 5 Breakdown